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STATE OF CALIFORNIA

TRANSPORTATION AGENCY

DEPARTMENT OF PUBLIC WORKS

DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMENT

RESEARCH REPORT

NO. M & R 631133-9

Prepared in Cooperation with the U.S. Department of Transportation, Bureau of Public Roads May, 1968

STATE OF CALIFORNIA—TRANSPORTATION AGENCY

RONALD REAGAN, Governor

DEPARTMENT OF PUBLIC WORKS

DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMENT

5900 FOLSOM BLVD., SACRAMENTO 95819

May 1968
Final Report
M & R No. 631133-9

Mr. J. A. Legarra
State Highway Engineer
Sacramento, California

Dear Sir:

Submitted herewith is the final research report on the Project:

Statistical Quality Control

of

Highway Construction Materials

George B. Sherman
Principal Investigator

Robert O. Watkins
Co-Investigator

Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

REFERENCE: Sherman, G. B. and Watkins, R. O., "Statistical Quality Control of Highway Construction Materials", State of California, Department of Public Works, Division of Highways, Materials and Research Department. Research Report 631133-9, May, 1968.

ABSTRACT: A summary of the findings of several interim reports on statistical quality control of highway construction material is presented. The advantages and limitations of the present control procedures are discussed. The work done to date indicates that statistical specification can be used to the advantage of the Highway Engineer.

During the study some of the problems identified that need additional attention were: personnel training, reproducibility of tests, preservation of engineering judgment, and cost of administration. Possible solutions to these problems are discussed including determining the precision of test method and procedures for assuring that a laboratory is in operational control.

One specific procedure, quality control by the moving average using control charts, is proposed. It is anticipated that this procedure will provide control without increasing cost while at the same time supplying management information in the form of charts and graphs.

KEY WORDS: Quality control, statistical quality control, construction materials, sampling, statistical sampling, control charts, construction control

ACKNOWLEDGMENTS

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The authors also wish to express their appreciation to the personnel of the Bridge and Construction Departments of the California Division of Highways for their assistance in obtaining data for these investigations. Special thanks are extended to the members of the Pavement, Concrete, and Foundation Sections of the Materials and Research Department for their assistance in performing the tests, analyzing the test results, and reviewing the interim reports.

The research work reported herein was accomplished under the Highway Planning and Research Project F-1-1 in cooperation with the U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

CONTENTS

INTRODUCTION

The great increase in highway construction work which was experienced during the 1950s and early 1960s resulted in rapid advancement of construction methods, with emphasis being placed upon high production. Testing and control procedures did not keep pace and this resulted in a slight reduction in overall quality. However, the highway industry was challenged and, through readjustment of control procedures, improvement in quality was made.

To date, specifications have been of the absolute type with considerable reliance being placed upon the experience of the engineer and his ability to select representative samples. This system has drawbacks, particularly under the stress of an increasing tempo of construction and lack of trained inspectors. In an attempt to improve specifications, it was suggested that the highway engineer consider adopting statistical quality control (SQC) procedures. The first step in this direction was taken by the United States Bureau of Public Roads who held workshops on quality control throughout the nation in the fall of 1963. At these workshops the Bureau proposed that the state highway departments research the subject of using statistical control methods.

In the spring of 1964, the California Division of Highways submitted a research proposal intended to determine the control limits to be used in statistical specificiations for nine construction items. The research has been completed on these nine items and eight interim reports containing the findings relative to these construction items have been completed, and are listed in the Bibliography.

OBJECTIVES

This study was initiated to:

1. place the California Division of Highways in a more knowledgeable position with regard to the use of statistical procedures for construction control;

2. evaluate the reproducibility of the testing and sampling methods in current use;

3. estimate the practicality of using specifications that contain acceptance limits determined by using statistical concepts.

CONCLUSIONS

1. The results of this research clearly show that there can be many advantages to statistically oriented specifications. It is anticipated that in the future such specifications will provide the construction engineer with more reliable data for judging quality; will be a means of assuring more uniformity of specification interpretation and enforcement from project to project; will provide management with information in the form of control charts, bar graphs, et cetera, to quickly evaluate the quality of materials being used on one or several projects. In addition, as end point specifications become more universally used, statistical control by the contractor is a means to assure himself that the product will comply.

2. The present construction specifications which involve fixed single limits and representative sampling procedures were surveyed by the use of random sampling procedures and it was found that in no single instance was there strict 100 percent compliance. This does not mean that the materials were not satisfactory for the purpose intended but rather that representative sampling introduces a significant bias in favor of acceptance. This was found to be particularly true of resampling procedures. It was concluded that the acceptance of a small percentage of some out-of-specification material did not significantly affect the adequacy of the engineering structure but rather represented a judgment factor normally applied by engineers to the work that they are responsible for.

3. The study indicated a need for systematic procedures to assure that sampling equipment, testing equipment, and the operator techniques are in operational control. Such methods are available in the literature.

4. Test methods used on highway materials in many cases do not contain a statement of reproducibility. Such statements based on adequate statistical data are necessary in order to compare results from different laboratories on a sound basis. It was found in the study that one single variance value did not represent the repeatability of a testing procedure but rather that the repeatability may be strongly affected by the magnitude of the test results.

5. It was concluded from this study that some of the major problems which will be encountered in the implementation of the quality control procedures in highway construction will be:

a. Most of the present specifications were written with the intent of using representative sampling and undefined re-sampling procedures; therefore acceptance levels will need to be revised if random sampling, with carefully defined re-sampling procedures, is to be employed.

b. Unprocessed highway materials, such as imported borrows, are often obtained in their natural condition from local sites and the contractor has very little control over the quality of the material. Such materials are less conducive to statistical controls than are processed materials, such as bases and surfacing materials.

c. There is serious apprehension by many engineers that statistical quality controls will significantly increase engineering costs. There is a feeling that the present products are satisfactory and, therefore, any changes in method should result in the same or lesser cost.

d. Many highway engineers and technicians have limited technical knowledge of the terminology and technology of statistical quality control.

6. It is concluded that adequate statistical control specifications can be devised to cover most highway materials. It is believed that this can be done and the present quality level maintained without a significant increase in the cost of control. As a matter of fact, if the speed of highway construction increases, it is a tool that will be necessary to assure actual control.

PROCEDURE

For each construction item surveyed, the sampling variance, testing variance, and the variance inherent in the material were determined. The majority of this research was accomplished by randomly selecting 50 sampling locations on three separate construction projects for each item. On a Statewide basis, 18 construction jobs were used to examine 6 specification items. At each sampling location, duplicate samples were taken side by side and later divided in half, thus providing four independent test results for each of the 50 locations. There were 200 test results from each project and a total of 600 test results for each item examined.

The duplicate sampling provided a measure of the sampling error. Duplicate tests on split samples provided a measure of the variance introduced by the splitting and testing process, and the 50 test locations on each project provided a measure of the basic variance in the process or material.

All the field sampling and testing completed for this research was independent of and in addition to the normal job control testing. Only material which had been accepted by construction forces was sampled for this research.

In addition to the field items studied, zinc coating of CMP and asphalt penetration test results were evaluated from the control test records on file. Even though random sampling procedures were not employed for these items, the results are still considered valid since in both cases every lot of material was tested for quality, thus reducing the possibility of bias in sampling. Records on file were also used in evaluating portland cement.

DISCUSSION

General

Statistical control procedures, with particular emphasis on random sampling in lieu of representative sampling, have been receiving increased attention in recent years. This attention can partially be attributed to the trend towards end point specifications combined with the increased production of the modern high speed construction operation. The majority of our present quality tests are based upon an inspector using certain stipulated testing procedures. These procedures have not always kept pace with the increased tempo of today's fast moving construction.

Many of the present procedures require that the inspector make some judgment decision regarding the quality of material entering the work. With the increased volume of highway construction, we find the well trained, experienced inspector has received additional assignments and is often assisted by an inexperienced aide or trainee. Innovations in future construction work will further hasten the obsolescence of today's testing methods and make the experienced inspector's job more difficult.

Traditionally, highway and bridge construction has been controlled by method or prescription type specifications containing some end point controls. This has caused some contractors to demand "Tell us what you want and we will give it to you, but don't interfere with the method we plan to use." Also, as implied by Foster and Stander(1), the engineer, by using a method specification, can find himself

(1) Refers to list of References at end of text.

in the position of being a party to the control. He is then in a difficult position if rejection of the final product becomes advisable.

Probably the engineer's biggest concern over abandoning method specifications is that there are certain qualities of materials which do not lend themselves to an end point specification. Consequently, end point tests are not available to measure many of the particular qualities needed. In attempting to control the quality of concrete, the only reasonable end point controls we have at present are the 7 to 28 day flexural and compressive strength tests; whereas the qualities of durability, low shrinkage, sulfate resistance, et cetera, often are more important, especially insofar as a highway pavement is concerned. Besides, who wants to make a decision to accept or reject concrete 7 or 28 days after it has hardened? At present, these latter qualities can only be controlled by controlling the aggregate characteristics, water/cement ratio, cement chemistry, percent of entrained air, and other related factors. If such a material is to be accepted on end results alone, some new tests will have to be devised. Procedures to be followed in the event the structure or item does not comply with the specification must also be fully defined.

Until end point specifications can be developed, the construction engineer will have to continue to rely on some method specifications in order to assure the quality of construction. These specifications can be and are being improved.

One of the first steps in developing improved specifications is to learn more about the limitations of our present specifications. An important overall finding of this research is that, when evaluating a product by random sampling, 100 percent compliance with the current specification is not always practical or even possible. Some of the reasons for this apparent lack of control are:

1. "Representative" Sampling - It was found that choosing sampling locations using a "selective" procedure will not necessarily provide an accurate representation of the material. The difference between the test results of "representative" samples (used for final control) and random samples can be seen in Figure 1. The average percent relative compaction ($\overline{X}$) for the final control samples was higher than the average for the randomly chosen samples, thus indicating that some of the material was satisfying the specification when, in fact, it was not.

2. Resampling - It is an accepted practice to perform a "check test" to verify a test result. Since

these check tests are only performed to verify failing and not passing results, this procedure is biasing the results in favor of acceptance. Figure 2 graphically presents this problem and, partially at least, explains the differences shown in Figure 1. In this example the quality of the material - which could be aggregate, compacted embankment, or any other item - is at such a level that the first sample has a 50 percent chance of falling below the specification limit and a 50 percent chance of acceptance. If a failing result is obtained on the first sample and the material is resampled, the 50-50 ratio still applies but as can be seen in the figure the probability of obtaining one passing result from the first two samples is 75 percent. Thus, re-sampling does not change the quality of the material, but it does increase the probability of acceptance.

3. Restrictive Specification - Specifications are sometimes written with a specific item or project in mind. When these requirements are specified for other projects, with different materials or conditions, they may be too restrictive. For example, assume that a job specification limits the maximum slump of concrete to 2 inches and a portion of the project contains heavily reinforced structural sections. Because the engineer is aware that 2 inch slump concrete, with the particular materials available for his project, will result in rock pockets and other difficulties, he accepts concrete with a slump outside the specification limits. This is obviously the only sensible action he can take.

4. Inadequate Measure of Quality - Some specifications are so restrictive that they cannot be met even on well controlled projects. This can result in an important specification being ignored. For example, the data from both this random survey and actual job control records indicate that a significant percentage of accepted concrete aggregate does not meet all the requirements for gradation. Since the other control tests, such as soundness of the aggregate and compressive strength of the concrete, are within accepted limits, the concrete is judged to be of good quality. Therefore, the present specification for gradation of aggregates is judged to be in itself an inadequate measure of quality. Concrete is an excellent example of a material whose quality is controlled by a series of empirical tests, no single one of which is sufficient to measure overall quality of the final product.

There are, no doubt, many more possible explanations for the acceptance of less than 100 percent compliance. Each of them provides additional evidence of the need for an engineering judgment factor in the specifications.

Even after considering the problems of noncompliance, it is realized that the current specifications provide a satisfactory working document for construction but there is a need, indeed pressure, to improve the specifications in order to obtain a more uniform interpretation on all construction projects. The results of this study indicate that statistical quality control (SQC) procedures, such as those employed by other industries, may be used to advantage on many control problems.

Statistical Quality Control

Often statistical control procedures are based on the assumption that the samples are drawn from a normal population. This does not mean that a few results will plot in the familiar bell-shaped pattern. However, a histogram of 3,000 or 4,000 results can be expected to approach normality. As seen in Figure 3, the results of the 4,620 penetration tests for asphalt closely approach this normal distribution. Results from other control tests, such as strength of concrete, consistency of fresh concrete, and thickness of zinc coating, also approach normality. It can, therefore, be concluded that it is theoretically possible to use established statistical control procedures for the control of some construction items.

Many governmental agencies and industries utilizing SQC at the present time have shifted the quality control responsibility to the producer. The buyer makes his purchase based on a statistically sound end point specification. For this process to function effectively, the producer must maintain complete quality control records and charts and make them available to the buyer at all times.

Procedural checks are, of course, necessary so that the owner can be sure that the contractor's operation is actually under positive control. After five years of SQC experience, one governmental agency has concluded that the advantages outweigh the disadvantages. This agency, however, does its own quality control work.[2]

Problems

There are several problems that will require solutions before statistical quality control procedures can receive widespread adoption.

1. Technical Training

One problem which must be considered is technical training. Many construction engineers and inspectors are unfamiliar with the technology and terminology of statistical quality control. To exemplify this, reference is again made to Figure 1 which illustrates the difference between statistical control methods and present construction control procedures. The "random" curve represents the test results obtained for this research. The "final control" curve represents the test results of the "representative" samples and resamples chosen in the presently accepted manner and used for actual acceptance of the work. Thus, we have two representations of the same material which do not appear to agree. Engineers, who normally think in terms of results from representative samples, will require training in order to properly use random results.

The problem of training is not limited to highway engineers. Recently Mr. Ted Busch, Vice President of the Dundick Corporation, wrote an article titled "The Mess in Measurement" in which he stated: "We lack a language for communication with other disciplines. We lack technicians who can reliably provide data. We are subject to fatuous instrumentation claims. And, we have allowed the American love of novelty and fad to becloud measurement practices."(3) If this problem can be found in the precise tool manufacturing industry, it can be expected to be magnified in the field of highway construction.

The California Division of Highways has made a start in the area of training. During the course of this project, statistical control procedures have been discussed by many engineers throughout the Division. The subject has been included as part of a one week materials training course conducted four times each year for engineers from various departments within the Division of Highways. Also, one 40-hour training class on statistics, conducted by a professor from the University of California, was completed by approximately 20 engineers from five departments within the Division. These researchers have been impressed with the willingness of many engineers to obtain training on this subject.

2. Engineering Judgment

The next problem for consideration is one which is inherent in the native local material which must be used for highway construction. The large variation in the characteristics of the native material throughout an area the size of the State of California makes it very difficult to prepare a single specification that will be applicable throughout the entire State and still assure a reasonable degree of control.

Consequently, final decisions are often required for selecting local material on each project. These decisions must be made by experienced engineers and must be based on their knowledge of the effect the particular material will have on the overall final products.

Many examples can be cited where engineering judgment is required in the field; the following is just one. An experienced engineer would be very concerned about obtaining the highest possible density of asphalt concrete when it is placed just before the winter rains begin; the same pavement, if placed in the late spring, would be consolidated and sealed by traffic during the warm, dry California summer which should allow for greater compaction variance without harm to the pavement structure. There are many factors which contribute to the durability of asphalt concrete. While some factors, such as aggregate gradation and asphalt content could be adequately controlled statistically, to subject all factors to normal statistical control procedures appears, at this time, to be unwise.

The solution is to recognize that there is no great, immediate need to apply statistics to the control of every construction item. We should proceed in those areas where these controls can be used to the greatest advantage.

3. Revising Present Specifications

The third problem is often recognized and has to do with the specifications themselves. Most of the present specifications and test procedures were not written with the intent of using a random or statistical sampling procedure. One proposed statistical specification requires that all aggregates be sampled using random procedures.(4) In another section of the same specification is found the following: "Insofar as applicable, AASHO T-2 is to be used in sampling aggregate." AASHO Designation T-2 makes no reference to random sampling but rather makes several references to representative sampling. In fact, the following quotation from T-2 would be incompatible with random sampling:

> "Samples from railroad cars should be taken from three or more trenches dug across the car at points that appear on the surface to be representative of the material."

Such examples of conflict are found throughout specification sampling procedures. Since it has been well established that statistical control procedures should not be applied unless samples are selected in a random manner (ASTM E-105), the establishment of new specification limits and test methods will be required.

The precision and reliability of various test methods will be of increasing importance with the adoption of statistical specifications. Some of our test methods have statements of precision included in the procedures; it will be necessary to include similar information in other test methods. In this study it was learned that the repeatability of some test methods is dependent upon the range of values obtained and thus a single value cannot be given for the precision of a test method. For example, the repeatability of the R-value Test was found to be 2.8 R-value units (R1S)* when testing processed aggregate base material which had an average value of approximately 80 R-value. The repeatability of the R-value procedure, when testing unprocessed aggregate subbase material, was found to be 4.3 R-value units (R1S) when the average value was 73. To obtain a specified degree of precision, therefore, it is necessary to average more R-value results when testing subbase material than when testing base material. This example is presented only to illustrate the complexity of the problem of defining testing accuracies.

Reference 5 contains a proposal that will daily provide some assurance that an asphalt laboratory is in operational control. It will no doubt be necessary to develop other procedures for laboratory control in the near future.

4. Control of Costs

Another problem is the often expressed concern of many engineers that the adoption of statistical controls will result in considerably increased construction control costs. The field engineer now makes a decision to accept or reject material on relatively few test results. This low sampling and testing frequency is practical because the engineer has an understanding of the construction that is underway and can increase or decrease the testing frequency as needed.

After studying various established statistical sampling procedures, such as Military Standards 105 and 414 (6-7) it is often concluded that the adoption of this type of sampling plan would result in a considerable increase in sampling. In a proposed statistical specification for gradation of aggregate base material, a sample size of "... five random samples of in-place material ..." was required from each day's construction.(8) While five gradation tests per day may be tolerable under some conditions, this number would usually result in increased control costs. If the same principles were applied to all control tests, the cost of construction control would significantly increase. Obviously, if the present control procedure has been successful in obtaining good quality construction, a significant increase

* Reproducibility one standard deviation

in the present sampling frequency would be hard to justify.

A good example of the utilization of statistical specifications with no increase in cost is California's recent shift from the sand volume method to the nuclear gage for relative compaction determination. The sand volume method is slow and decisions were based on individual results with no allowance for testing or sampling inaccuracies. Now enough readings can be made to apply a modified statistical control procedure. This has been done with no change in the overall control costs and has provided the engineers with more reliable results.

In the long run one would expect many applications of statistical control procedures to result in reduced costs. Contracting agencies are presently performing many tests on materials which are processed or manufactured elsewhere, such as asphalt, cement, steel, et cetera. In most cases, similar tests have already been performed by the producer on this material. There seems to be little need for the contracting agency to duplicate the quality assurance measures performed daily by the producer. It should be possible to establish a systematic program with the manufacturers of these items so that inspectors could make a periodic surveillance of a plant's control procedures and records. With such a program, use of the material would be based on certification by the producer. Audit sampling and inspections could be made at the jobsite to verify the adequacy of the plant's control or to assure that contamination or other damage had not occurred.

Programs of this type are a regular part of the military quality control program.[9] For a number of years a certification program has been used by the California Division of Highways for asphalt, cement, and steel; however, the control procedures used by the refineries and mills are presently validated only with a large number of check samples. No doubt the procedure could be improved and testing reduced by formalizing an agreement between the producers and the contracting agency.

One Approach to SQC

There are many ways in which statistics can be used to control quality. One approach which ongoing research has indicated may be a useful control tool employs the moving average of the five most recent test results (or some other number when conditions warrant)*. The advantages of using the moving average approach are:

1. More information is available to the engineer than is available when considering only a single test result.

*Active Research Project "Applications of Statistical Quality Control Methods", HPR F-1-3, Calif. Division of Highways, Materials and Research Department.

2. Randomly occurring "extreme values" are identified.

3. When plotted on a control chart, trends in material quality or uniformity can be readily observed.

4. When compared to a full statistical specification, fewer tests are required for control.

5. The precision of the test result can be controlled depending upon the number of tests included in the running average. This increases the reliability of the decision making process.

The moving average is used with the assumption that the material is produced by some process which results in reasonably uniform material with comparitively low material variance over a period of time and that random variations from the norm are acceptable. The moving average would be much more applicable to the control of a processed aggregate than to the control of a pit run material where large sudden nonrandom variations are expected to occur; thus, the specification designer must consider the nature of the material available for use in construction.

The foregoing procedure has been formalized and is presently a part of the California Division of Highways Materials Manual. The method is titled "Statistical Means For Determination of Specification Compliance Using Moving Averages and Control Charts" and is shown as Appendix A.

Benefits From Research

Side benefits which have resulted from this research are impressive. While the staff of the Materials and Research Department have long used statistical procedures in their research work, they have, as a result of this study, become more aware of the advantages of employing these procedures. There has been a general improvement in the design of experiments and such procedure as analysis of variance has been used for evaluating improvements and determining the precision of a test method. There appears to be an increase in the overall efficiency of research work being conducted by this staff.

This interest is not limited to research engineers alone; we find field inspectors maintaining control charts and calculating standard deviations. Even though control charts and standard deviations are not new to many inspectors, an increased interest in these methods has been observed.

This increased interest in field control procedures is rapidly extending to the contractors and material producers. Rock producers have been observed using newly developed control charts and one producer reports using the charts in making a decision to increase their quality control efforts. Since quality control procedures have proven to be extremely valuable to other industries, it is not surprising that the highway construction industry is already finding valuable applications.

As a direct result of this research work we find those individuals concerned with highway materials communicating in terms of materials variances with an increased understanding. Some engineers who were initially skeptical of this project now have a wait-and-see approach. Most engineers are now willing to think in terms of specifications which allow for a percent of material outside a given limit. In fact, this very thinking allowed the Division of Highways to revise the requirements for compaction of embankment using a modified statistical procedure.

Almost all test data gathered indicate that there is more variation in test results than had been anticipated by most experienced engineers. After reading the interim reports for this project, several construction engineers have indicated that, for the first time, they have a measure of the variation in test results. This study has also resulted in recognition that testing laboratories require an overall operational assurance program as opposed to only a periodic equipment calibration.

Future Development Work

As pointed out in this report, many problems remain before statistical control procedures will receive widespread adoption in the highway industry. As a first step, it is thought that statistical concepts should be developed and applied with no immediate transfer of the control responsibility to the contractor. After SQC has been established, consideration could be given to the transfer of production control to the contractor or producer. This transfer would need to be programmed over several years to provide the contractors with enough time to efficiently adjust their staffing and operations.

While in the process of developing statistical specifications, it should be possible to utilize statistical procedures to increase the management efficiency of current control methods. In order to hold down the cost of sampling and testing, moving averages can be used for control. The use of the moving average or chain sampling is not new and has been reported by others. [10-11-12] The moving average can be used by the engineer to make a decision to accept or reject material based on the cumulative information from several recent acceptable lots of material (see Figure 4).

As stated in the interim reports on this project, it is recommended that the engineer be permitted to make a judgment decision when an occasional test result is outside the specification limits providing the moving average indicates that the particular procedure is in operational control.

In addition to utilizing a moving average, it is further proposed that control charts be used (see Figure 5). A properly maintained control chart allows for an immediate review of the material being used in the construction and can be easily understood at all levels. It is proposed that the control chart be accepted on a trial basis as a contract document in lieu of the great volume of test reports and other records which must be maintained with the current system.

Due to the increasing obsolescence of the current quality control methods, new procedures must be developed. In addition to providing more accurate measurements of quality, SQC may also provide future specification writers with a more complete understanding of the test values that are practical for field control. It will also provide a measure of the effectiveness of new construction materials, procedures and methods. If the utilization of SQC is first limited to those construction operations for which it appears most applicable, it should prove to be a very useful addition to construction control.

Finally, the use of statistical quality control specifications is only one step in a quality assurance program. Much work is needed in the highway field to re-evaluate the significance of present tests and to devise new and more meaningful measurements. To do this will require systematic evaluation of performance. Thus, to reach the final goal of better specifications and control is going to require the combined efforts of engineers from areas of design, construction, maintenance, and materials in addition to the specification writers.

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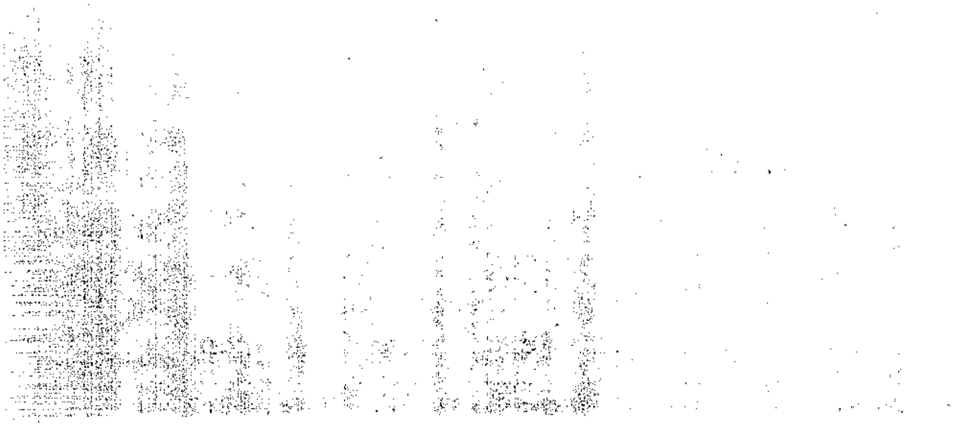
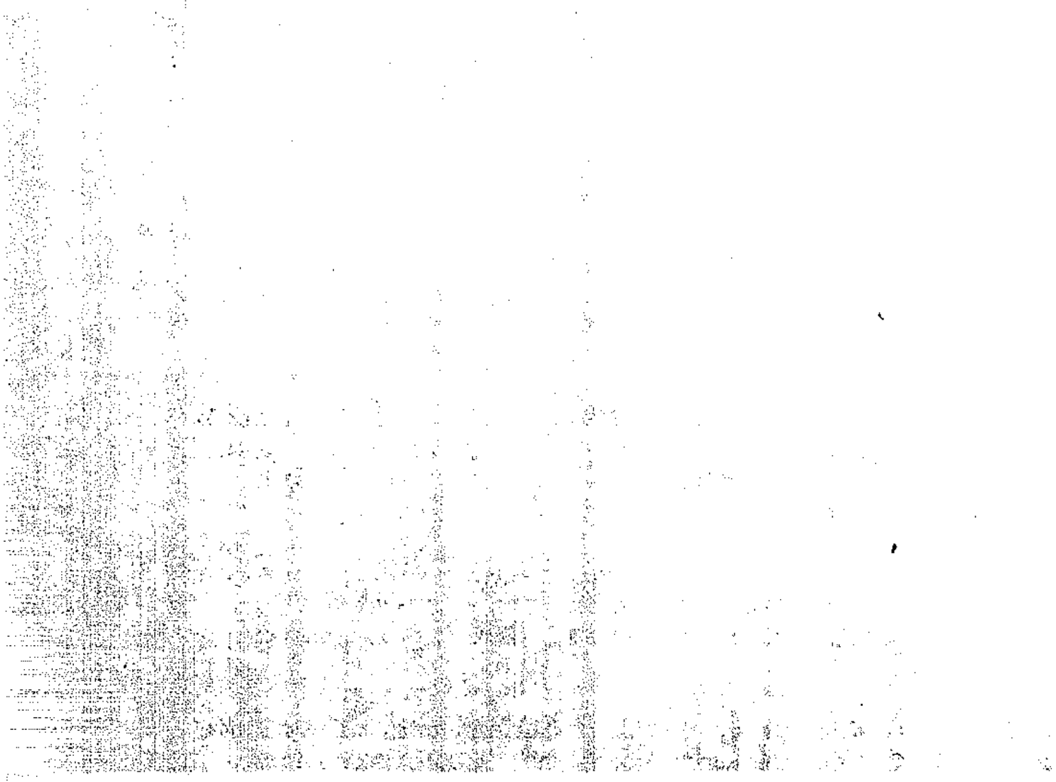




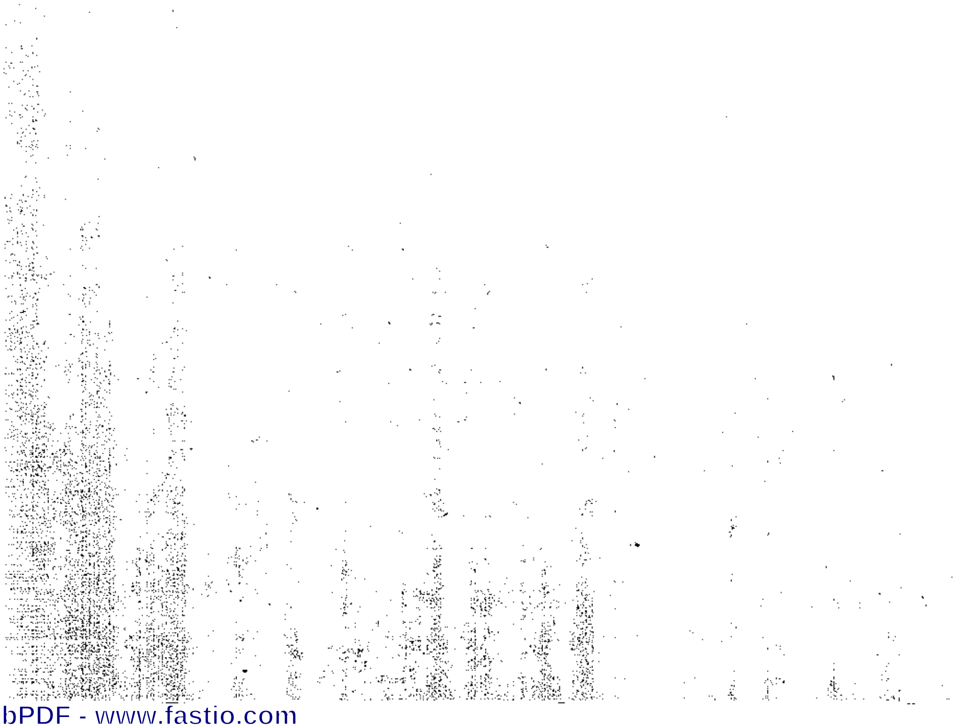


Figure 1

REPRESENTATIVE VS. RANDOM SAMPLING

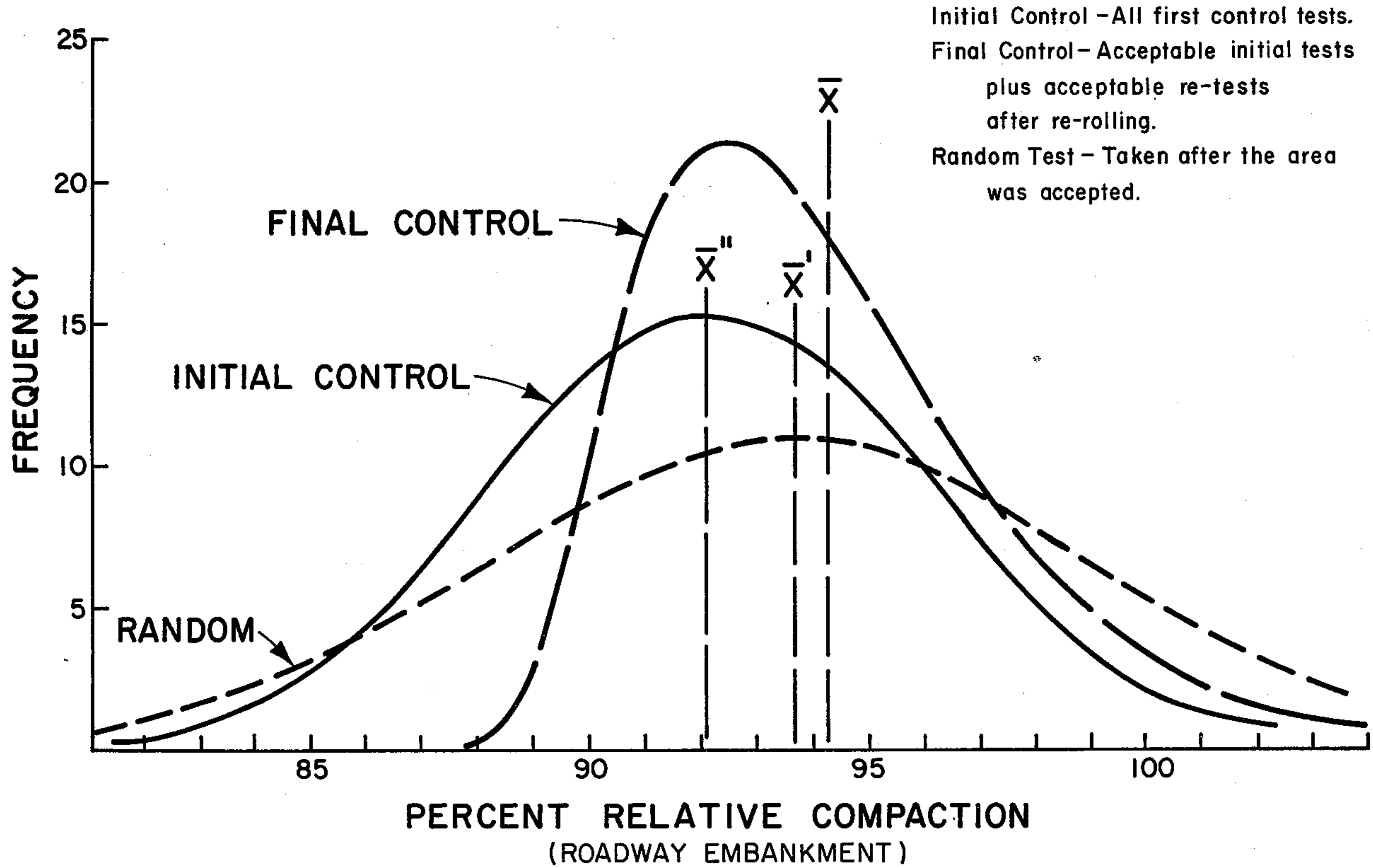
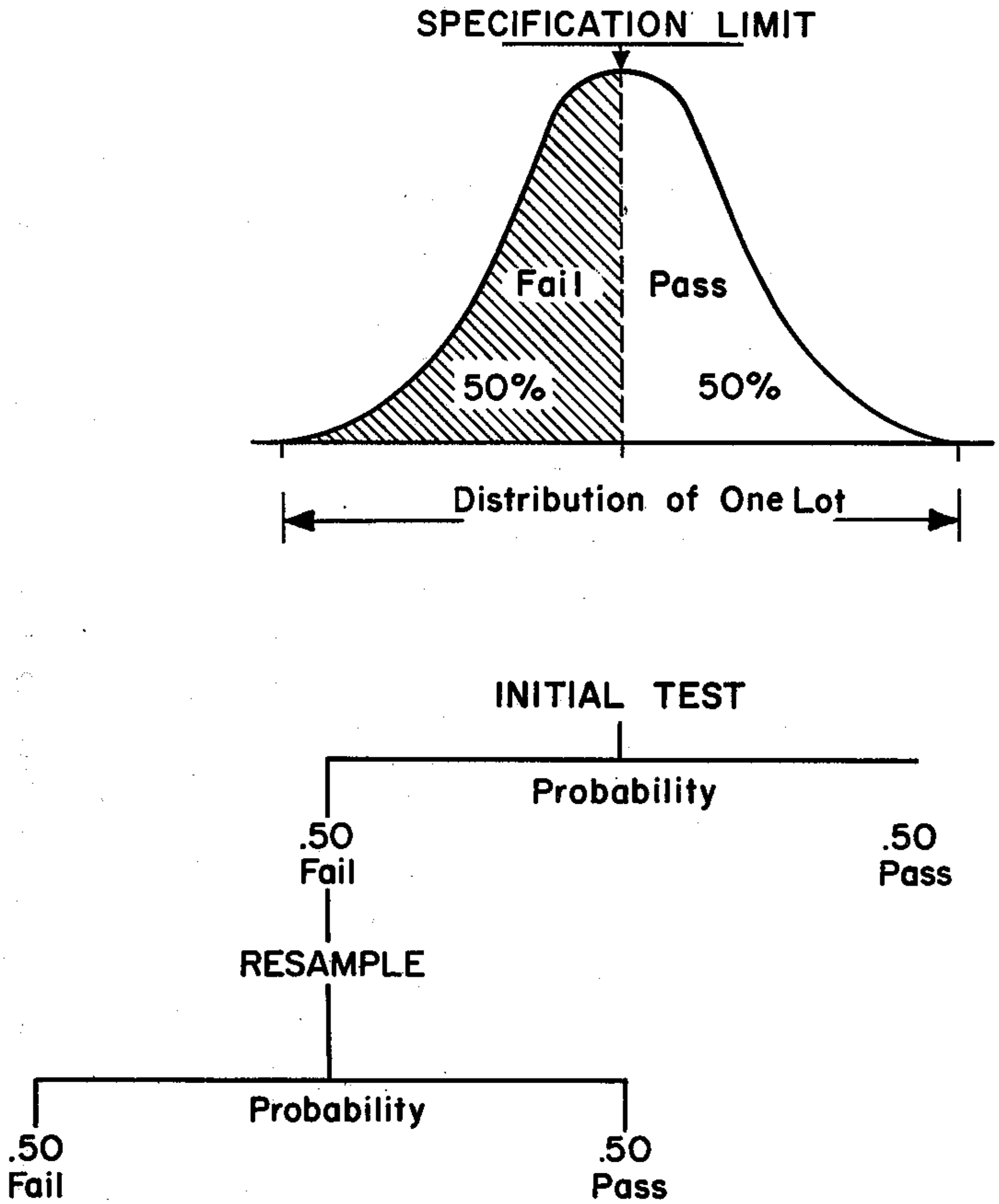


Figure 2

PROBABILITY OF ACCEPTANCE WHEN RESAMPLING

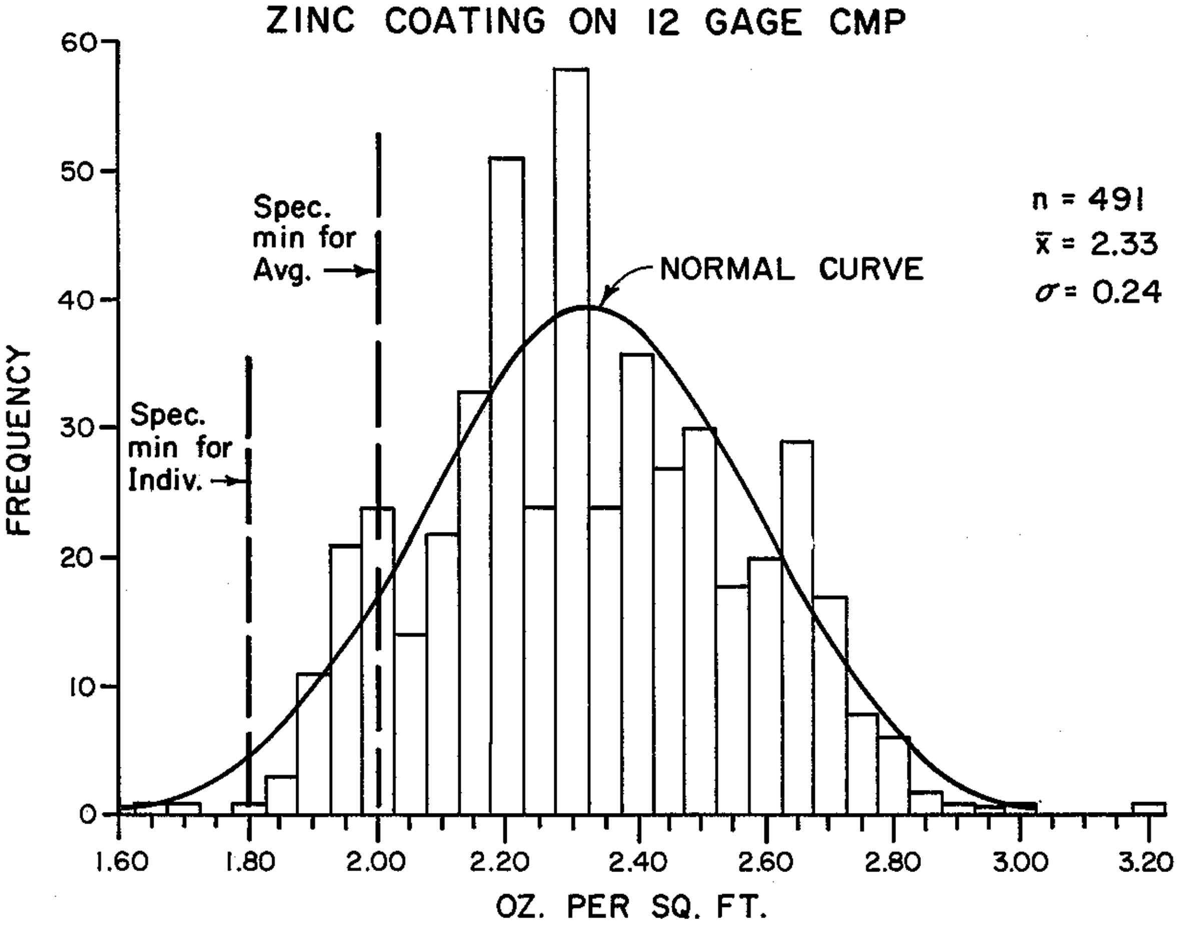


OVERALL PROBABILITY

Passing $.50 + (.50 \times .50) = .50 + .25 = .75$

Failing $.50 \times .50 = .25$

Figure 3


ZINC COATING ON 12 GAGE CMP
FREQUENCY
OZ. PER SQ. FT.
Spec. min for Avg.
Spec. min for Indiv.
NORMAL CURVE
n = 491
$\bar{x}$ = 2.33
σ = 0.24
60
50
40
30
20
10
0
1.60
1.80
2.00
2.20
2.40
2.60
2.80
3.00
3.20

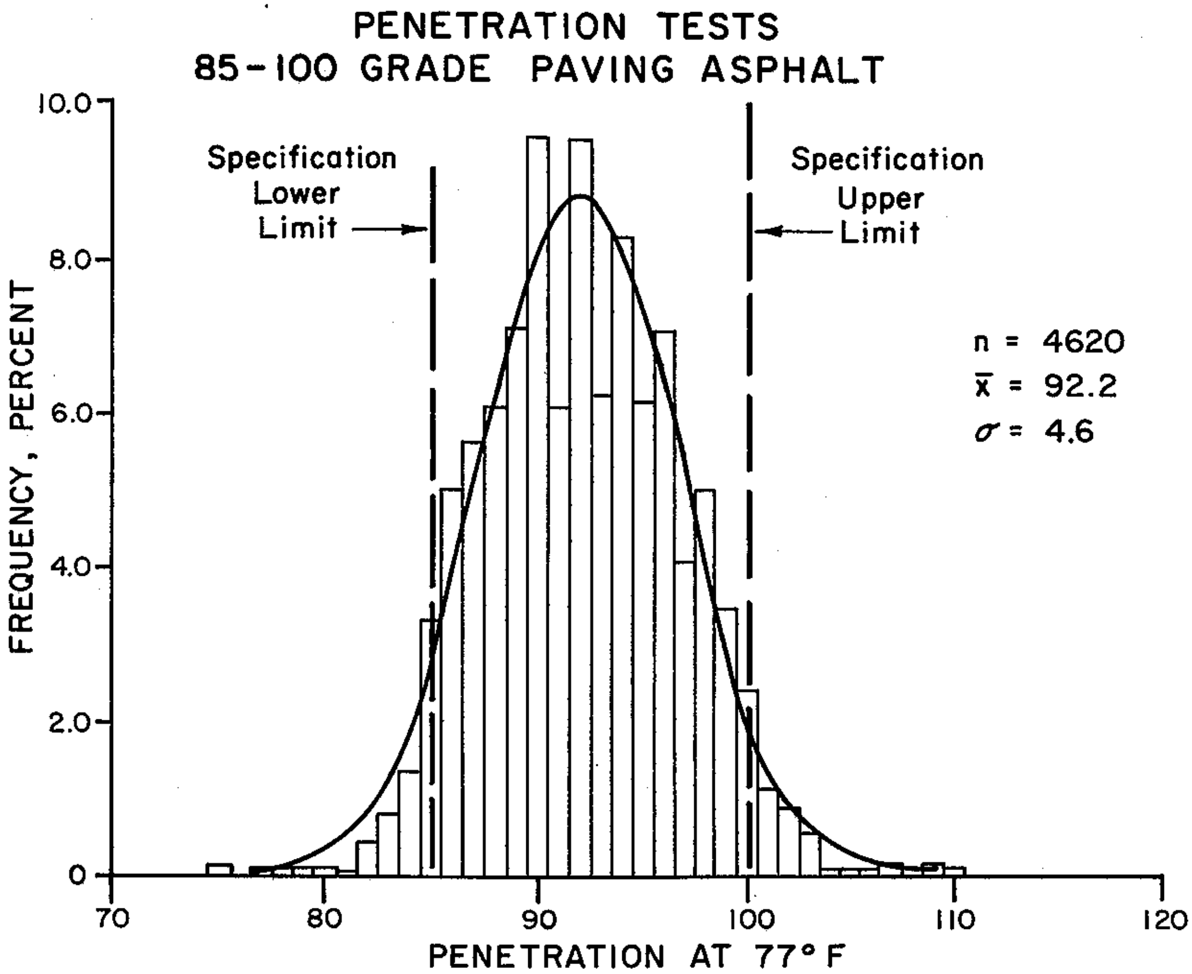
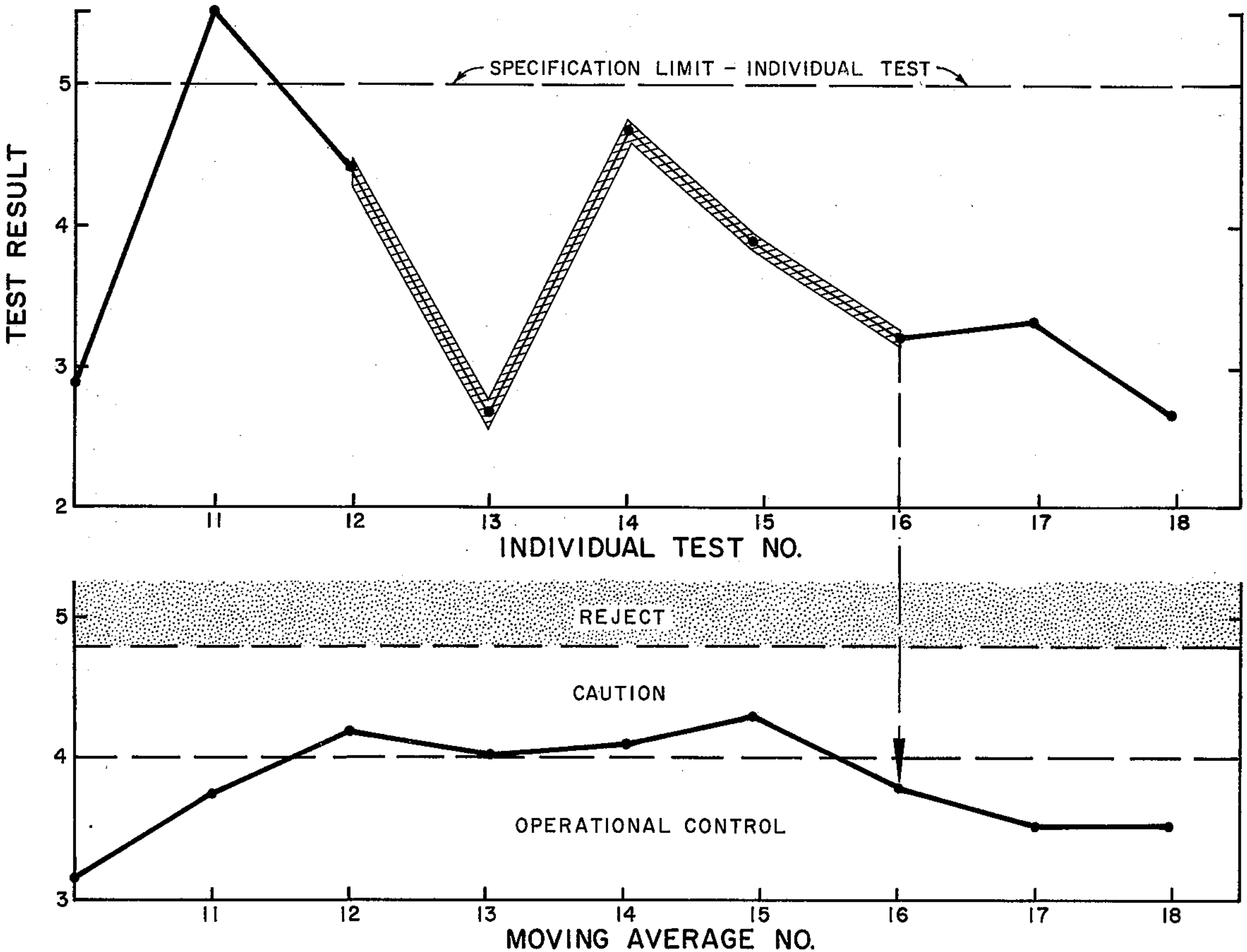

PENETRATION TESTS
85-100 GRADE PAVING ASPHALT
FREQUENCY, PERCENT
PENETRATION AT 77° F
Specification Lower Limit
Specification Upper Limit
n = 4620
$\bar{x}$ = 92.2
σ = 4.6
10.0
8.0
6.0
4.0
2.0
0
70
80
90
100
110
120

Figure 4

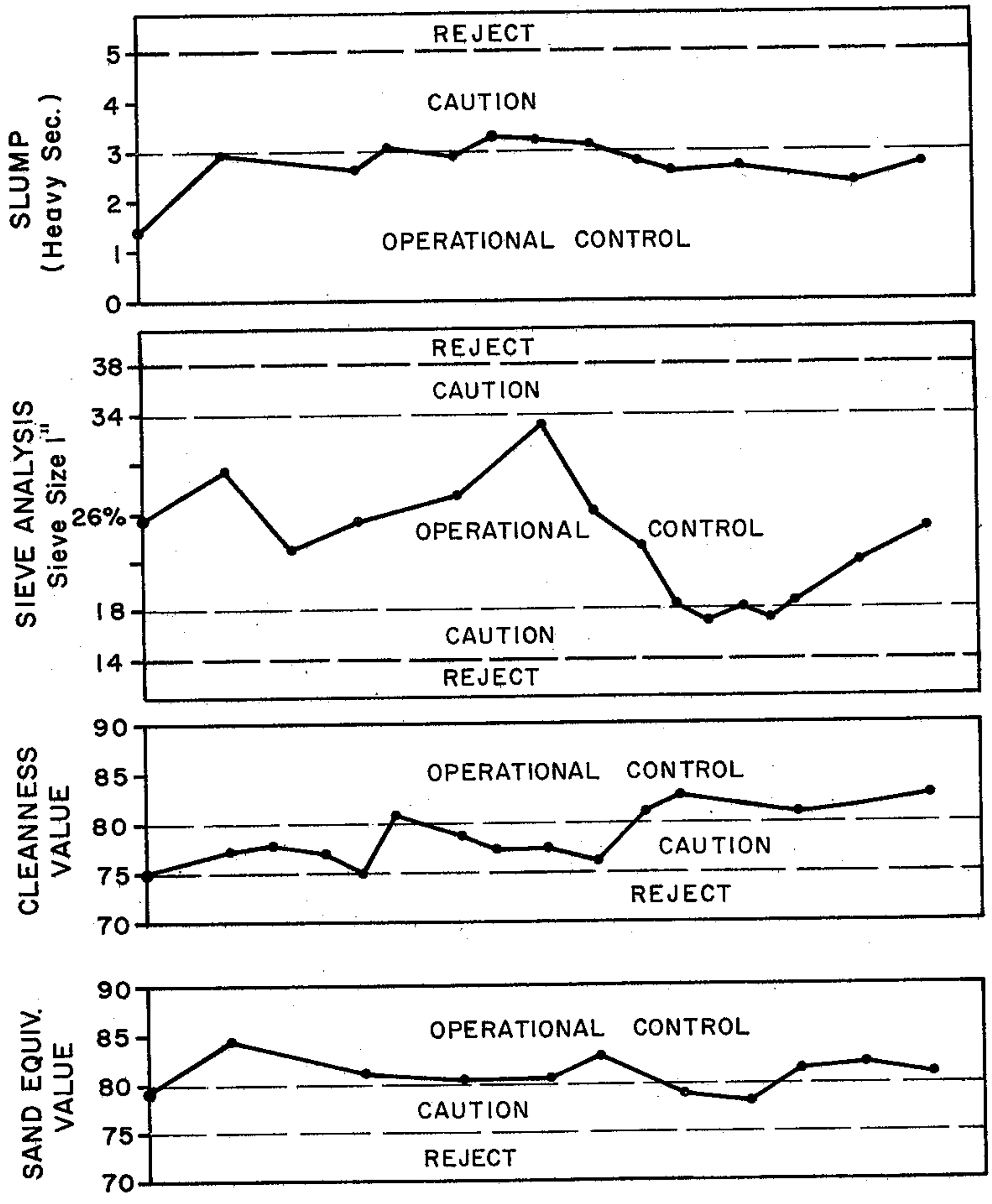
MOVING AVERAGE

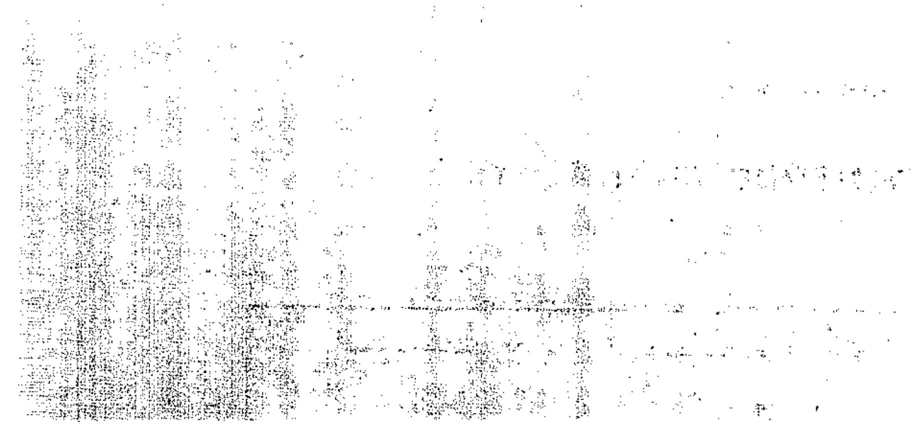


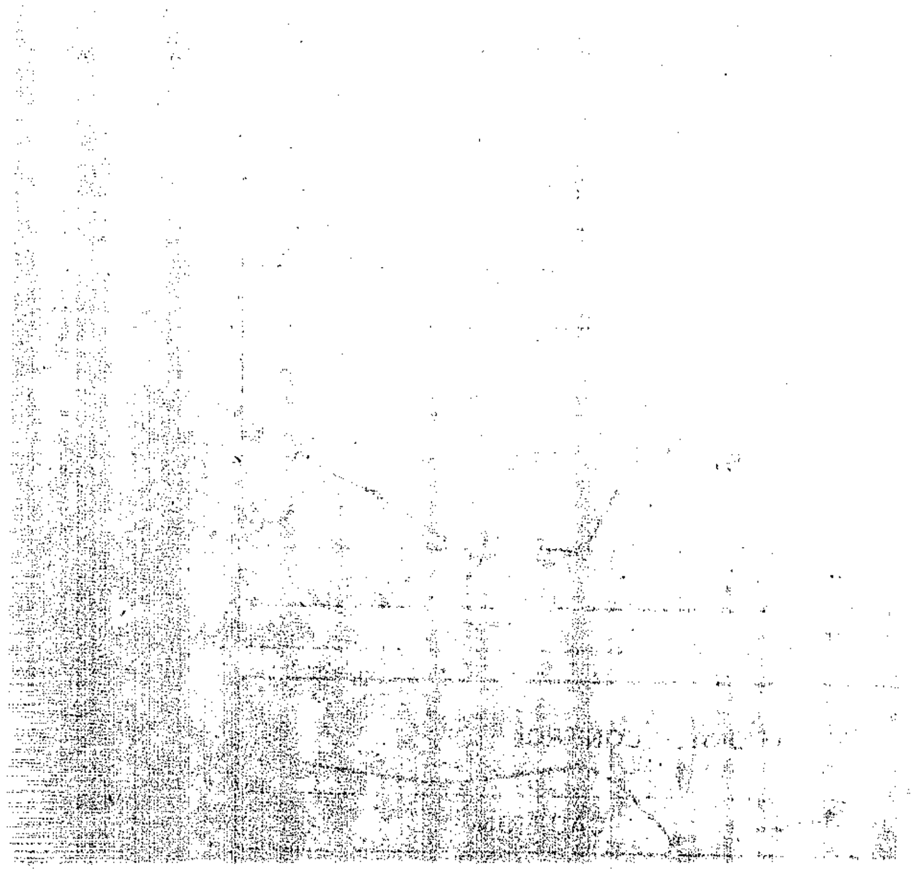
The decision to accept lot 16 is based on the average of test results 12 through 16. For lot 17 the average of 13 through 17 would be used, etc.

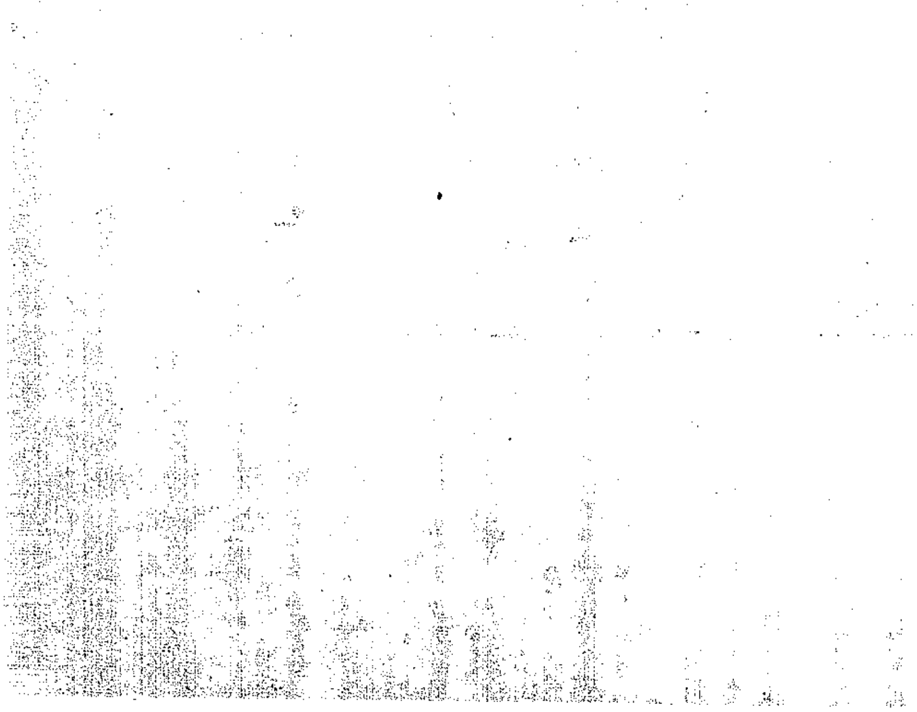
Figure 5

CONCRETE CONTROL CHART









APPENDIX A

MATERIALS AND RESEARCH DEPARTMENT

State of California
Department of Public Works
Division of Highways

Method No. Calif. 908-A
March 15, 1968
(2 pages)

STATISTICAL MEANS FOR DETERMINATION OF SPECIFICATION COMPLIANCE USING MOVING AVERAGES AND CONTROL CHARTS

SCOPE

This method describes procedure for using statistical means for determining specification compliance of materials on a construction project.

PROCEDURES

A. Definitions

1. Test Result - An individual result used in determining acceptance of material. In some cases, such as the Ball Penetration Test (Test Method No. Calif. 533), each test result is the average of three or more individual readings. The number of readings may vary with individual test procedures depending upon the accuracy of the test.

2. Moving Average - Unless otherwise specified, the moving average is the average of the four most recent test results representing accepted material plus the test result from the material being considered for acceptance.*

3. Control Chart - A chart for the presentation and analysis of data. In the case of the Moving Average, the data are obtained from more than one test result. Control charts provide visual evidence that a process is in operational control.

B. Initial Determination

1. The moving average at the start of the job is not determined until the second test result is obtained; however, if the material is accepted, the first test result shall be shown as the first point on the control chart. For the first test result, only the specification limits for the individual test shall apply and this test result, if the material is accepted, shall be included with the second test result for calculating the moving average. The moving average for

* These results will be rounded to the same number of significant figures as in the individual test result. When the decimal fraction to be dropped is less than 5, round down; if greater than 5, round up; and if it is a 5, round either up or down to the even number (see Examples Nos. 1 and 2).

the second through the fourth test results is the average of all results representing previously accepted material plus the test result from the material being considered. From the fifth test result on, definition A-2 applies. Any test result representing rejected material is not included in the calculations for the moving average to be plotted on the control charts.

C. Procedure When Individual Results are Out of Specifications

1. Generally, specifications will require both individual tests and moving average results to be within specified limits. At the discretion of the engineer, an individual test result outside the specification limit may be waived providing the moving average is within limits, however such a test result must be included when calculating moving averages. If the moving average exceeds the specified limits, the material does not meet specifications.

2. If the moving average is out of specifications and the contractor has taken significant steps to correct any deficiencies, the next individual sample that meets specifications after production is resumed may, at the discretion of the engineer, be used to start a new moving average series.

D. Noncontinuous Moving Average

1. The moving average for any one material does not necessarily have to be continuous for the complete project. At the discretion of the engineer, a new moving average series may be started when there are periods of inactivity, changes in materials or processing, change in job mix formula, etc.

E. Frequency of Sampling

1. A guide to the frequency and location of sampling is given in the Construction Manual.

REFERENCE

Division of Highways Construction Manual

End of Method No. Calif. 908-A

March 15, 1968

EXAMPLE CALCULATIONS FOR MOVING AVERAGES FOR CONTROL CHARTS

These examples are intended as a guide to the Resident Engineer and are not a part of Method No. Calif. 908.

This guide shows an optional use of a caution zone with the control chart. The caution zone, though not a part of the method, is intended as a warning area on the control chart where prudent forethought should be exercised to minimize risk of going out of specifications. Caution zones are arbitrarily selected and used to indicate when the process appears to be going out of control. No rules or set criteria are given because materials variance throughout the State may cause test results in some areas to approach the limits and still consistently be in specifications. For this reason, the area defined as the caution zone will be set by the engineer.

All tests on material incorporated into the project should be shown on the control chart. Any tests on material rejected and not incorporated into the project should not be shown on the control chart.

Tests on progress samples may, at the discretion of the engineer, be plotted on the control chart as individual test results but are not to be included in the moving averages.

EXAMPLE NO. 1

Calculations to Determine Moving Averages for the Sand Equivalent Test
(See Figure I for a plot of the data)

Assume a specification for individual test of not less than 73 and a moving average not less than 75. The caution zone for this example was arbitrarily set between 75 and 80.

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EXAMPLE NO. 1 (continued)

Test No.	Date	Individual Test Result (Min.73)	Sum	Moving Avg.* (Min. 75)	Rounded To
1	8-11-67	79**	---	----	---
2	8-14-67	85	164	÷ 2 = 82.0	82
3	8-16-67	84	248	÷ 3 = 82.7	83
4	8-18-67	72 Waived and accepted by Engr.	320	÷ 4 = 80.0	80
5	8-22-67	80	400	÷ 5 = 80.0	80
6	8-24-67	75	396	÷ 5 = 79.2	79
7	8-25-67	74	385	÷ 5 = 77.0	77
8	8-28-67	68	369 ÷ 5 = 74 Material rejected and results not shown on control charts.		

Operation discontinued after Test No. 8 and significant step(s) taken by the contractor to correct deficiency before additional material was accepted.

9	8-29-67	79**	---	----	---
10	8-31-67	80	159	÷ 2 = 79.5	80
11	9-5-67	81	240	÷ 3 80.0	80
12	9-7-67	83	323	÷ 4 80.7	81

* These results will be rounded to the same number of significant figures as in the individual test result. When the decimal fraction to be dropped is less than 5, round down; if greater than 5, round up; and if it is a 5, round either up or down to the even number.

** Show this test result as the first value on the moving average control chart.

EXAMPLE NO. 2

Calculations to Determine Moving
Averages for 1-1/2" x 3/4" Concrete Aggregate
(Maximum Variation of Percentage of Material Passing 1" Sieve)
(See Figure II for a plot of the data)

Contractor's Proposed Average (Job Formula) = 26%
Assume the specifications allow an individual test variation of ± 14% and a moving average variation of ± 12% from the average submitted by the contractor.

The caution zone for this example was arbitrarily set between ± 4% of the lower and upper limits.

Test No.	Date	Individual Test Result (Limits 12% to 40%)	Sum	Moving Avg.* (Limits 14% to 38%)	Rounded To
1	6-5-67	27**	---	----	---
2	6-6-67	24	51	÷ 2 = 25.5	26
3	6-8-67	28	79	÷ 3 = 26.3	26
4	6-12-67	29	108	÷ 4 = 27.0	27
5	6-14-67	35	143	÷ 5 = 28.6	29
6	6-16-67	34	150	÷ 5 = 30.0	30
7	6-20-67	42 Waived and accepted by Engr.	168	÷ 5 = 33.6	34
8	6-22-67	38	178	÷ 5 = 35.6	36
9	6-26-67	40	189	÷ 5 = 37.8	38
10	6-27-67	42	196	÷ 5 = 39 Material rejected and results not shown on the control charts.	

Operation discontinued and significant step(s) taken to correct deficiency before additional material was accepted.

* These results will be rounded to the same number of significant figures as in the individual test result. When the decimal fraction to be dropped is less than 5, round down; if greater than 5, round up; and if it is a 5, round either up or down to the even number.

** Show this test result as the first value on the moving average control chart.

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EXAMPLE NO. 2 (continued)

Test No.	Date	Individual Test Result (Limits 12% to 40%)	Sum	Moving Avg.* (Limits 14% to 38%)	Rounded To
11	6-29-67	25**	---	----	---
12	6-30-67	28	53	÷ 2 = 26.5	26
13	7-5-67	20	73	÷ 3 = 24.3	24
14	7-7-67	25	98	÷ 4 = 24.5	24

* These results will be rounded to the same number of significant figures as in the individual test result. When the decimal fraction to be dropped is less than 5, round down; if greater than 5, round up; and if it is a 5, round either up or down to the even number.

** Show this test result as the first value on the moving average control chart.

Figure I

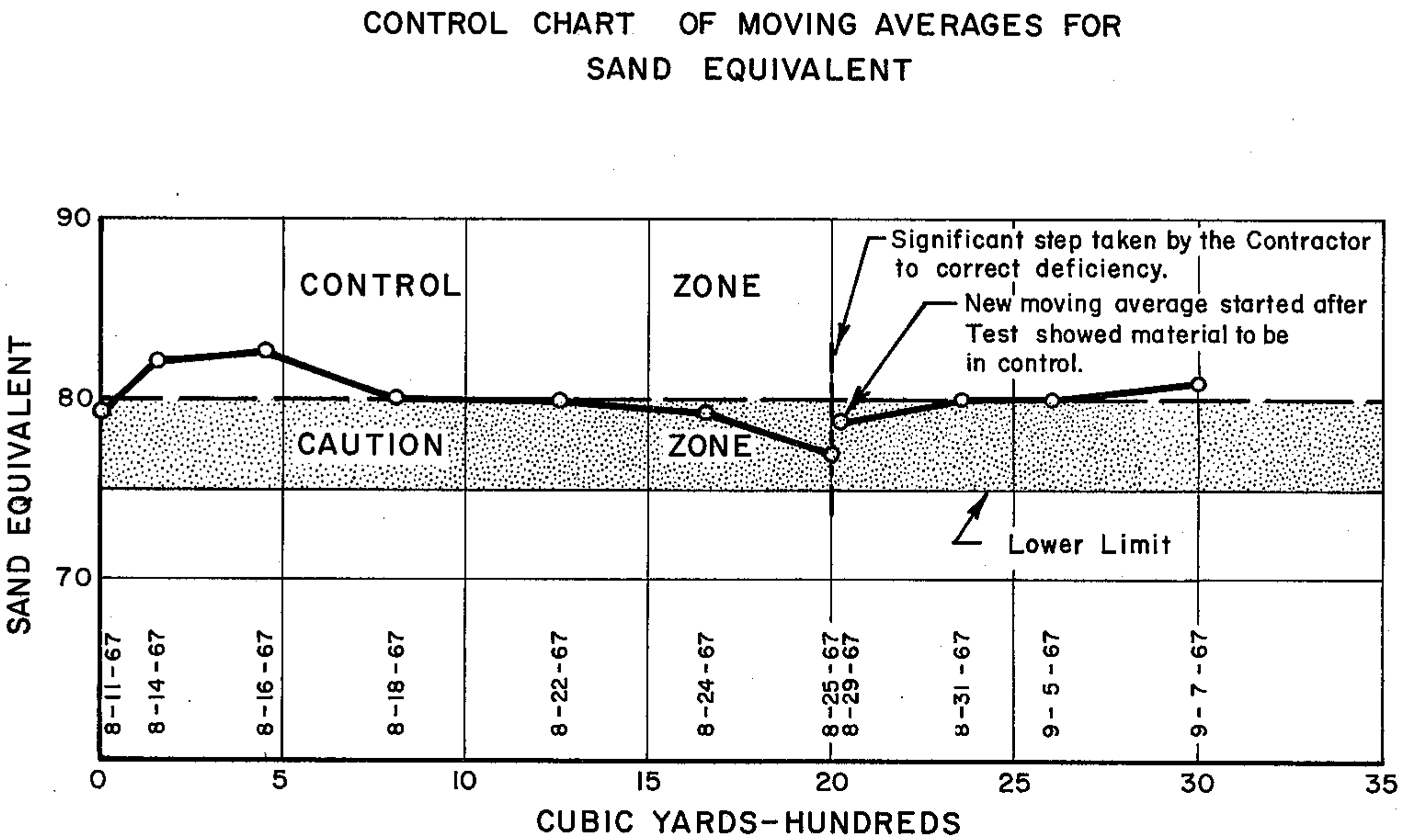
CONTROL CHART OF MOVING AVERAGES FOR
SAND EQUIVALENT
90
80
70
SAND EQUIVALENT
CONTROL
ZONE
CAUTION
ZONE
Significant step taken by the Contractor to correct deficiency.
New moving average started after Test showed material to be in control.
Lower Limit
8-11-67
8-14-67
8-16-67
8-18-67
8-22-67
8-24-67
8-25-67
8-29-67
8-31-67
9-5-67
9-7-67
0
5
10
15
20
25
30
35
CUBIC YARDS-HUNDREDS

Figure II

CONTROL CHART OF MOVING AVERAGES FOR GRADING ANALYSIS